PIARC and fixed fire-fighting systems: A report on working group activity

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1 ABSTRACT

Fixed Fire Fighting Systems (FFFS) in road tunnels have obtained much broader acceptance in recent years. As a consequence, there have been multiple FFFS installations, numerous FFFS test programs and much greater attention given to FFFS in the tunnel fire & life safety community. Codes and Standards for the most part do not require FFFS in tunnels. For example, one international standard introduces FFFS as an optional system for consideration. In the near future, PIARC will publish a guide titled "Fixed Fire Fighting Systems in Road Tunnels: Current Practices and Recommendations" under the auspices of the PIARC Technical Committee C3.3 – Road Tunnel Operations (1). This paper provides an overview of that document and the work of the Working Group over the past eight years.

Subject material covered includes the following:

- A discussion of decision factors that will enable key stakeholders to determine whether or not to install FFFS.
- Design Considerations for installation of FFFS.
- Guidance on the selection and procurement of FFFS.
- Examples of the application of FFFS around the world.
- A broad overview of the research and analysis of FFFS.

The material covered presents an international understanding of the application of FFFS in a tunnel environment.

2 INTRODUCTION

2.1 Background

PIARC, The World Road Congress, generates guidance documents related to roads and highway networks. There are several PIARC technical committees, including Technical Committee C3.3 Road Tunnel Operations. The guide "Fixed Fire Fighting Systems in Road Tunnels: Current Practices and Recommendations" has been developed under the auspices of the C3.3 Committee through Working Group 4: Fire Safety.

This paper is intended to raise awareness of the efforts of Working Group 4 on behalf of the Technical Committee. The full report is scheduled for publication in the fall of 2015 and significantly expands upon the information found herein.

2.2 FFFS – A definition

Although the term FFFS includes all types of fire-fighting systems in tunnels, this paper addresses water-based FFFS only. Typical FFFS use a system of pipes and valves to bring water to discharge nozzles. Most systems fall into one of two categories. Deluge Systems generate larger droplets, control the fire principally by surface cooling, and generally operate at lower pressures. Water Mist Systems, on the other hand, operate at higher pressure, generate smaller droplets and promote more effective gas cooling.

Traditional deluge systems are found in Japan and Australia and consist of conventional deluge nozzles in zones that can be activated either automatically or by the operator from the tunnel operation control room. Water mist systems are also designed with zones, although the zone length may differ from that used in deluge systems. Both of these systems have been applied to tunnels, although deluge systems without additives represent the vast majority of the installed systems.

2.3 A history of fire suppression in road tunnels

Historically, FFFS have not commonly been provided in road tunnels, although their use by specific authorities in the USA, in high risk tunnels in Japan and in tunnels in Australia has been routine for decades.

One of the first systems to be installed worldwide was in the City of Seattle, where the Fire Department made it a requirement to install FFFS in road tunnels. The first to be installed was a deluge system in the Battery Street Tunnel (State Route 99) in 1954. This is one of the oldest FFFS installations in the world and, even though it is 60 years old, still functions using nearly the entire original infrastructure.

Despite these precedents, the rest of the world has shied away from the provision of such risk reduction measures in road tunnels. In 1999 when the PIARC guidance "Fire and Smoke Control in Road Tunnels" (9) was published, Fixed Fire Fighting Systems (FFFS) were not recommended and were not widely accepted due to fears of creating adverse conditions in a road tunnel environment. These historical concerns have been studied via full scale fire testing and operational experience over the past 30 years and a number have proven to be unfounded. Historical concerns and their current status are listed in the Table below.

HISTORICAL CONCERN	CURRENT STATUS
Water could cause explosion in petrol and other chemical substances if not combined with appropriate additives.	Operational experience has shown that the application of water does not create explosions. Tests with pool fires have generally not caused explosions except for limited test results during exceptional test conditions.
There was a risk that the fire was extinguished but flammable gases would still be produced and may cause an explosion.	Explosions from flammable gases have not been realized in the numerous tests that have been undertaken.
Vaporised steam could hurt people.	Steam generation has not been evidenced in full scale testing. While theoretically steam generation may instantaneously occur local to the fire site, any steam generated would be quickly cooled by the FFFS and the area of influence extremely limited.
The efficiency of flame extinguishment was low for fires inside vehicles.	It is correct that flame extinguishment by FFFS may not be possible where the fire is in a compartment, however, the application of FFFS removes heat from the surface of the compartment reducing the rate of fire growth and prevents fire spread from the vehicle of origin such that the impact of any fire event is reduced.
The smoke layer would be cooled down and destratified, so that it may cover the whole tunnel leading to loss of life. And Visibility was reduced.	For smoke to form a stratified layer the fire must be reasonably developed and the fire size large. This in itself would cause loss of life local to the fire site. Also, it is advised to commence FFFS operation as early as possible in the fire growth cycle. This enables the fire to be controlled and the fire size to remain small thereby assisting with the self evacuation of people. Further, FFFS is only one aspect of life safety and must be balanced with suitable egress provisions.
Installation and maintenance could be costly.	Installation and maintenance does attract a cost, however, operational experience has shown that this cost is much less than refurbishment of a tunnel after a fire event. Also the costs may be able to be offset against the deletion of other life safety elements.

As shown in the table above, while some of these concerns are valid, there can be significant benefit from the installation of FFFS for fire and life safety. With appropriate procedures and an understanding of the objectives of FFFS effects of these concerns can be minimised. Nevertheless, the installation of FFFS may not be an appropriate risk reduction measure for all road tunnels.

2.4 Current position

The current PIARC Report “Fixed Fire Fighting Systems in Road Tunnels: Current Practices and Recommendations” seeks to put FFFS into perspective for Administrative Authorities, Tunnel Operators, Designers and Emergency Services by providing guidance on whether to consider providing it, and the design and operational considerations required if it is installed.

The report discusses the functional impact FFFS can make to the performance of tunnel fire safety systems. Information is presented about the types of systems available, their use in road tunnels for various countries, and provides advice on the design and selection of appropriate FFFS.

Where FFFS are adopted, it is essential that they are correctly designed, installed, integrated, commissioned, maintained, tested and operated. It is also recommended that they are activated in the early stages of a fire to minimise fire growth and to provide the desired effectiveness.

3 DECISION FACTORS

The decision process for the installation of a FFFS varies from country to country. In Japan and Australia they are commonly installed, whereas in other countries they are considered on a case to case basis. A risk assessment is then often used to justify the need for FFFS, since currently most countries do not mandate the installation of a FFFS. Regardless, when deciding whether or not to install FFFS, the following must be considered:

- Compliance with regulations, guidelines and safety standards, including legal considerations;
- Life safety including the functions and roles of FFFS in the safety concept;
- Asset protection including availability of the transport link;
- Flexibility for additional traffic regimes such as Dangerous Goods Vehicles;
- Fire-fighting response;
- The ability to adequately operate and maintain the system, including the roles, positions, and responsibilities of the stakeholders;
- Cost benefit analysis covering installation capital cost and/or life cycle cost, as well as the impact on sustainability;
- The need to always consider system reliability and redundancy.

If it is ensured that FFFS are activated in a timely manner, it may be possible to optimise other fire-life safety measures without compromising the safety requirements. FFFS are active systems that must be maintained to a high standard to operate as intended. In addition, FFFS may be implemented to reduce the heat release rate of the design fire, which can have other beneficial effects such as allowing the required capacity of the tunnel ventilation system to be reduced.

FFFS was installed in the Northern Link Tunnel (Stockholm, Sweden) as a mitigation measure against the consequences of fire during traffic congestion which would permit the longitudinal ventilation system to be retained. FFFS was installed in the Felbertauern Tunnel (Austria) to protect the fresh-air duct, which is situated above the traffic space, as this serves as egress route in case of fire. Limitation of fire growth was an important factor in the decision to provide FFFS in the Roermund Tunnel (Netherlands) and the E4 Bypass Stockholm (Sweden).

The impact of HGV fires can be reduced using FFFS, making it possible for a tunnel to allow the passage of dangerous goods transport, where otherwise this would not be permitted. This was the main reason for installing FFFS in the Gnistängs Tunnel in Gothenburg (Sweden).

FFFS can enhance asset protection by reducing the risk of collapse of a tunnel, e.g. for underwater tunnels or where important infrastructures are located above the tunnel. This was part of the consideration for installing FFFS at critical locations on the M30 Tunnels in Madrid (Spain).

FFFS can also support asset protection by reducing the duration of tunnel closures after a fire. Critical arteries need to be protected. This was clearly demonstrated by the Heavy Goods Vehicle (HGV) fire in the Burnley Tunnel Toll Road (Melbourne, Australia) in 2007 (6). The fire potential was estimated to be greater than 100 MW but was reduced to less than 20 MW by rapid activation of the deluge type FFFS system (6). Consequently, the tunnel was reopened within few days. Additionally, a main objective to install FFFS on some of the privately owned tunnels on the A86 ring road in Paris (France) was to minimise down-time subsequent to a fire.

If FFFS are used as a compensatory measure e.g. for life safety or for asset protection, careful consideration must be given to their reliability, availability and maintainability (RAMs) when assessing their benefit. Appropriate redundancy may be required to achieve the availability criteria desired. Certainly, the consequences of failure of FFFS to operate on demand must be considered.

FFFS will, in most circumstances retard fire growth but not extinguish it. Extinguishment of the fire requires human intervention, typically by the fire brigade. FFFS are also advantageous when the fire-fighter response could be delayed. Though the fire department may arrive at the tunnel in a timely fashion, it may take 15-20 minutes or longer to reach the fire and commence firefighting.

By adding water to the environment, the application of FFFS will have a negative impact on visibility. Moreover, smoke stratification, especially in the activated suppression zone, will be degraded if not destroyed by employing FFFS. This may hinder way-finding and increase smoke concentrations in the downstream zone. However, when FFFS are activated as soon as possible, as they should be, the temperatures, heat-release rates (HRRs), and volume of smoke produced are reduced, which all have a positive impact on tenability conditions within the tunnel.

Although it has not been observed in documented events, activating FFFS could discourage people from leaving their vehicles. However, in the 2007 Burnley Tunnel fire (Melbourne, Australia, (6)), it was demonstrated that people could be persuaded to leave their vehicles when a FFFS is active. Irrespective of having FFFS, people need to be encouraged to leave their vehicles and to commence evacuation. Investigations have shown that there should be two independent types of cues and that the most efficient method is instructions from a person of authority (8). Cues can be given from public address (PA) systems, radio re-broadcast (RRB), sound beacons, guidance lighting, variable message signs, guidance lighting, contour lighting around doors and strobe lights.

4 DESIGN CONSIDERATIONS

The installation of FFFS impacts many aspects of the tunnel and tunnel systems, such as requiring additional water and drainage, space for additional equipment, and a means of control. FFFS in road tunnels also require fire detection. The potential benefit is to generally improve the safety level.

FFFS requires a water supply at a suitable pressure and capacity to provide for FFFS as well as hydrants or standpipes. FFFS would normally be operated in zones associated with the fire location for a prescribed duration, which defines the required volume of water to be provided either from a local water supply or from some form of water storage facility. Insufficient pressure may require the installation of booster pumps. Additional drainage requirements need to be provided such that the flow of water from FFFS plus additional water sources, such as hydrants that may operate simultaneously and any spills from vehicles, are removed.

The choice of system depends on space, drainage and water supply issues and the characteristics of suppression required in the particular tunnel. Mist Systems, for example, tend to use less water, so might be preferred where water supply or storage is problematic, or in retrofit applications where drainage capabilities may be limited. However, they require more power to drive pumps for the higher pressures.

To activate FFFS, some form of fire detection is required. It must identify the location of the fire and hence the zone or zones that need to be activated. Detection may be automatic or manual, and may include linear heat detectors, CCTV and similar. Automatic and manual detection systems are frequently combined to minimise false alarms. Following detection, the FFFS can be activated either automatically or manually.

The tunnel environment also has an impact on the design. Depending on climate, there may be a need to prevent freezing, such as trace heating, anti-freeze additives, circulation pumps with or without water heating, and insulation. Operation in sub-zero temperatures may lead to freezing of pipes and drain covers, compromising drainage. Water effluent discharge to local natural resources may also be an issue.

FFFS has an impact on the other systems in the tunnel, and consideration needs to be given for the various interfaces. Ventilation systems, for example, will be impacted in a number of ways: the interaction between water droplets and the airflow, and the reduction in heat release rate and air temperature. Traffic control may become more complex; visibility via CCTV may be impaired by the FFFS activation; tenability will be altered. These and other operational and technical features need to be reviewed with the impact of FFFS in mind. With regard to operation, FFFS should be activated as quickly as possible to inhibit fire growth. Thus, fire detection and determining the correct location are critical in achieving this result.

Other aspects that will influence the design include the need for redundancy of the systems by way of back up pumps, water supply contingencies and reliability of control systems. A reliability analysis should be undertaken during the design. Material selection is also important, noting that the system must operate for a long period of time in very hot conditions.

5 SYSTEM DEFINITION/PROCUREMENT

Specifying and procuring a FFFS for installation in a road tunnel involve particular performance and contractual issues. The PIARC report highlights key points that should be considered by the stakeholders, and by clients in particular, to avoid problems arising during projects. Some of these points are outlined here.

Clients need to consider first whether a particular FFFS should be specified or the choice left open to bidders. Useful published guidance is available to prepare the specification, but this will not necessarily take into account the circumstances of a specific tunnel. The installation of FFFS may be engineered in accordance with general industry standards, but the details will need adjusting for tunnel-specific issues. Alternatively, a FFFS contractor may offer a system that is effectively "off the shelf", having been engineered previously for another tunnel. In this case, attention should be given to how much additional design may be needed for the specific tunnel in question. An alternative or supplementary approach is to specify the actual fire-fighting performance to be achieved by the FFFS, defined in terms of parameters such as the heat release rate versus time, tenability conditions or maximum temperatures at specified points.

The effectiveness of any system will be uncertain unless appropriate testing or modelling is undertaken, or fire test results are already available for similar circumstances. If fire testing is to be undertaken, the test protocols will need to reflect the operating arrangements at the specific tunnel.

Road tunnels incorporate mechanical, electrical and traffic management systems, which are separate from but may have interfaces with FFFS. These interfaces are likely to be important factors to consider when preparing the FFFS specifications. In existing tunnels, there may be constraints on the positioning of FFFS components to avoid adverse effects on the existing installations.

The components of FFFS will need to be regularly inspected and tested. There are generally significant constraints on when such activities can take place in a tunnel, and the specification should therefore state any particular requirements and constraints. Associated with this, training of tunnel staff involved in operations and maintenance will be essential and will need to be addressed.

High system reliability is essential and the control system should be subject to strict integrity requirements. In countries with severe winter conditions, the system definition needs to include provisions to ensure that system operation is not impacted by the climate.

The desired life expectancy of a FFFS, before it is completely replaced, may be stated in the specification. It will vary for the different parts of the system and will depend heavily upon the maintenance regime and the tunnel environment. Some components will require replacement during the lifetime of the system, and the availability of spare parts therefore needs to be considered.

The requirements for testing and commissioning will need to be specified. The requirements for tunnel FFFS are similar to those for suppression systems in general. The requirements for the control system will potentially be more complex and will need to take into account the interfaces with other systems in the tunnel.

It is important that the requirements and approval process are clearly defined and understood by all stakeholders at the outset. The contractor may be unfamiliar with the highway standards and approval processes applicable for the country and tunnel in question. Where performance is specified, the acceptance criteria will constitute contractual obligations. Care is therefore needed to make sure as far as possible that the implications are understood by the contractor.

When assessing the cost of installing FFFS, the whole life-cycle costs should be taken into account. The capital cost of FFFS can vary widely between tunnels and countries depending on the circumstances. The cost of full scale fire testing, if required, is high. User costs include maintenance, spare parts, routine testing, training of personnel, operating costs, and energy costs.

6 SYSTEM APPLICATION

Australia has installed deluge systems into its road tunnels since 1992. Currently there are 19 tunnels with deluge systems in operation. The deluge zone length can vary with the tunnel width but it is generally about 20m in length. One or more zones can be operated simultaneously but in normally numerous zones are operated so that even if a vehicle straddles the interface between any two zones, it is still within the total deluge area. Current common practice is to provide a water discharge density of between 7.5 and 10 mm/min. Activation of the deluge system is usually by manual operation from a remote control room. Japan introduced deluge systems into its high risk expressway tunnels 45 years ago. Currently there are over 120 systems in operation. The Japanese deluge systems are designed for 6 mm/min. Some other countries, such as the USA and some countries in Europe, also have traditional deluge systems.

Water mist systems are fundamentally similar to deluge systems (i.e., the pipework consists of a water-filled mains pipe, manifold, deluge valves, dry feed main and branch pipes to which the nozzles are attached). The mains pipe is connected to a water supply and pumps generate the pressure. Water mist systems may vary with respect to their working pressures: i.e. low-pressure and high-pressure systems. The piping or tubing utilized in the system must be designed for the corresponding operating pressure. The primary difference between the high and low pressure systems is the percentage of smaller droplet sizes. The droplet size is inversely proportional to the pressure applied, and the momentum of the spray ejected from the nozzles. Spray from high-pressure nozzles typically has higher momentum than spray from low pressure nozzles.

The effectiveness of the mist system is based on a strong correlation between spray density, momentum and droplet size. The discharge rate for low-pressure systems is in the range of 1.1 - 3.3 mm/min ($l/min/m^2$) and for high-pressure systems 0.5 - 2.3 mm/min. Note that the design application densities are based on a density per unit area of coverage (mm/min). They are generally converted to other measures when discussing water mist systems, namely a volumetric density expressed as a flow rate per volume ($l/min/m^3$) by simply dividing mm/min by the ceiling height of the tunnel in metres. The length of each zone can vary from 20 m to 25 m and up to three zones can be activated concurrently.

There is no doubt that deluge systems are more effective than water mist systems when it comes to suppressing A-class fires (solid fuel). On the other hand, water mist systems are more effective on B-class fires (liquid), unless foam additives are used.

Water mist systems are superior at thermal management as they effectively cool the hot gases and encapsulate the fire radiation, thereby decreasing the heat fluxes acting on the structure and the risk for fire spread.

It should also be kept in mind that not only is droplet size important in largely determining the outcome, but so is the total potential energy (water density) delivered into the flame zone. Activation time and shielding of the fire are the two most important parameters to consider. Water delivery to the fuel while the burning area is still not too large is important.

One of the main advantages of the deluge system is the available operation history, in Australia and particularly in Japan. In these countries, it is difficult to find any adverse effects of these systems in the available literature. The main disadvantage is that very few large-scale tests have been performed with deluge-type systems.

Water-mist systems have accumulated an impressive list of large-scale tests. However, due to commercial reasons, the information from those tests is usually not fully available to the public. From the information that has been shown, it is clear that water-mist systems effectively reduce the gas temperature and heat flux, but the reduction of the heat release rate varies. In the majority of tests published, the reduction is about half the potential maximum heat release rate.

The consequences of false activation should be considered, as should system safeguards to prevent this type of event. The importance of preventing false activation was clearly demonstrated in the Central Artery North Area (CANA) Tunnel in Boston USA, where the deluge system was taken out of service due to several accidental activations.

Few cases of accidental activation or negative effects of FFFS systems have been reported. The smoke from fires in those cases where the system has been activated has been de-stratified only in the vicinity of the fire. There is no sufficiently supported technical argument against the use of water-spray or water mist systems in road tunnels. However, there is a lack of information from large scale tests on the effects of the FFFS on smoke production and production of toxic gases such as carbon monoxide.

The only argument that can be considered valid is that of investment and maintenance costs. However, seen in the larger context i.e., including the costs of fire damage, deaths and injuries, and loss of tunnel service, it is likely that the cost of a FFFS can be justified, at least in road tunnels carrying high volumes of traffic.

7 FFFS RESEARCH

Full-scale testing of FFFS in road tunnels has increased tremendously over the past fifteen years. Many of these programs have been extensive in nature, such as the 2nd Benelux Tunnel Fire Tests; the Runehamar Tests (2013); the Solit Test Programs, both 1 and 2 and the LTA Singapore Tests. In excess of 20 full scale fire test programs have been performed.

The need for these test programs have been driven by the complexity of the decisions behind the selection of the correct FFFS for the particular tunnel. The fire hazard in a tunnel is much different than that experienced in a building design/installation. Vehicle fires can be very large and intense events and can vary significantly depending on the traffic using the tunnel. As a result, a correct understanding of the objectives of FFFS needed to be founded upon full-scale experience. Additional complexities include the water application rate, zone length, effects on the tunnel user upon activation, etc.

Even with all of the complexities involved, there have been broad and general conclusions based on the results of these FFFS test programs:

- FFFS is likely to prevent the spread of fire from one target to another;
- When there is a stratified smoke layer, FFFS locally de-stratify the smoke layer to the roadway;
- FFFS reduce visibility within the zones where they are activated, even without fire;
- Radiation effects from a fire are reduced;
- Maximum gas temperatures are reduced and the region of tunnel impacted by high heat effects is significantly minimized;
- Fire HRR can be reduced;
- Steam generation is not sufficient enough to be considered a threat.

8 CONCLUSIONS AND RECOMMENDATIONS

Fire events in tunnels continue to have significant consequences for tunnel users, tunnel infrastructure, and the wider road network on society. FFFS can deliver user safety and infrastructure protection, but their use is not widespread for various economic, technical, political and social reasons. Should FFFS be adopted, the PIARC report will provide guidance on the decisions required and on the required design and implementation considerations.

Extensive testing has demonstrated that while FFFS have the ability to reduce the fire HRR and prevent the fire load reaching its full potential, high gas temperatures may still be reached that affect the structure or other infrastructure in the immediate vicinity of the fire. This has a direct link to choosing the correct design fire HRR for the design of FFFS to limit fire growth and the adoption of procedures to assure early activation of systems in the event of fire.

Final recommendations and conclusions include the following:

- Where FFFS are installed, it is essential that they are correctly designed, installed, and integrated into the tunnel system, as well as properly tested, commissioned, maintained, and operated.
- FFFS can and should, be activated in the very early stages of fire development before fire-fighting activities commence by trained fire fighters. This allows early suppression and minimises the potential adverse effects of the fire.
- FFFS should only be activated after confirming the fire location and with the incident vehicle stopped. Clear plans and procedures are necessary for tunnel operators to activate the FFFS, or effective automatically operated systems implemented.

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